On interference and non-interference in the SMEFT

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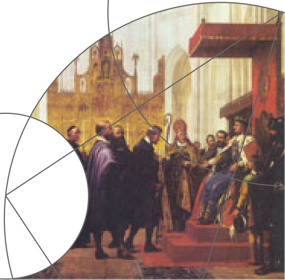
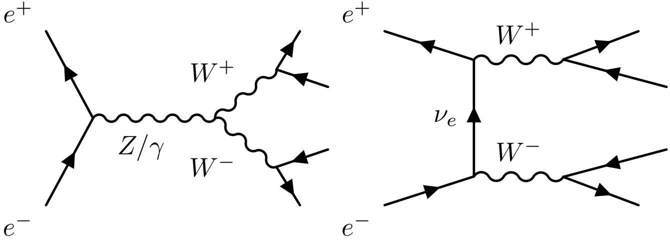


Outline

Based on arXiv:1711.07954 with M. Trott.



- Standard Model Effective Field Theory (SMEFT)
- Interference and non-interference in electroweak diboson production
- The narrow width approximation and the SMEFT expansion

Standard Model Effective Field Theory

Using the fields and symmetries of the Standard Model (SM), we add higher dimensional operators

$$\mathcal{L}_{\mathsf{SMEFT}} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \dots \qquad (1)$$

where

$$\mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \qquad \text{for } d > 4. \qquad (2)$$

$C_i^{(d)}$: Wilson coefficient
$Q_i^{(d)}$: Operator with mass dimension d
Λ: Scale of New Physics

Interference in the SMEFT

When the Standard Model (SM) and Beyond Standard Model (BSM) contribute to the same amplitude

$$A_{\mathsf{SMEFT}} = A_{\mathsf{SM}} + \frac{1}{\Lambda^2} A^{(6)} + \dots \tag{3}$$

where $A^{(6)}$ is an amplitude with one insertion of an operator from $\mathcal{L}^{(6)}$. The cross section

$$\sigma \propto |A_{\mathsf{SMEFT}}|^2 \sim |A_{\mathsf{SM}}|^2 + \frac{1}{\Lambda^2} A_{\mathsf{SM}} \times A^{(6)} + \frac{1}{\Lambda^4} |A^{(6)}|^2 + \dots \tag{4}$$

For small BSM effects the interference term dominates over the last term.

Non-interference in the SMEFT

When the SM and BSM do not contribute to the same amplitude

$$\sigma \propto \sum |A_{\mathrm{SMEFT}}|^2 \sim |A_{\mathrm{SM}}|^2 + \frac{1}{\Lambda^4}|A^{(6)}|^2 + \dots \qquad (5)$$

The leading BSM effects are suppressed by $\mathcal{O}(\frac{1}{\Lambda^4})$, the same order as operators of mass dimension 8 that do interfere.

Hard to measure!

More on non-inteference

The phenomenon of non-interference has been seen before in a QCD context (Simmons '89, Dixon and Shadmi '94). General statements can be made from helicity arguments:

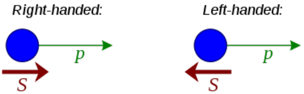
Non-interference statement

Four-point amplitudes with at least one transverse polarized gauge boson do not interfere at tree level in the massless limit.

Lately, similar reasoning has been applied to electroweak diboson production in the high energy limit (Azatov et. al. '16).

Helicity arguments

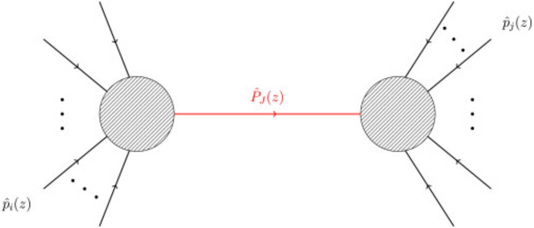
For massless particles we define helicity.



We put intermediate propagators on-shell:

$$h(A_n) = h(A_m) + h(A'_m) \tag{6}$$

where $n = m + m' - 2$.



Helicity arguments

Using little group scaling and dimensional analysis, we have that

$$|h(A_3)| = 1 - [g] \tag{7}$$

In the SM, $|h_3^{\mathrm{SM}}| = 1$, while for dimension-6 operators $|h_3^{\mathrm{BSM}}| = 3$.
For the SM at we can use helicity selection rules (from SUSY Ward identities) to show that

$$|h(A_4)^{\mathrm{SM}}| < 2 \qquad \text{(at least one vector boson)} \tag{8}$$

Helicity arguments

Summary:

- Helicity sums
- Three-point kinematics
- Helicity selection rules

Result:

$$|h_4^{\text{SM}}| = 0 \tag{9}$$

$$|h_4^{\text{BSM}}| = 2, 4 \tag{10}$$

when there is at least one transverse vector boson.

Softening the claim

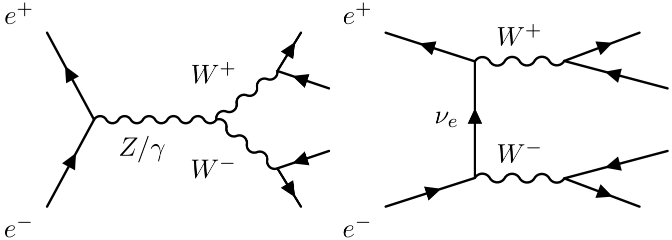
For electroweak diboson production we note that it holds:

- Only at tree level
- In the high energy limit, $\hat{m}_W^2/s \ll 1$
- For on-shell vector bosons

The statement will get loop and mass corrections.
In addition, on-shell massive gauge bosons are not formally physical.

The first two points have been considered.
We also take the last possibility into account.

Off-shell effects



We investigate three regions of phase space:

- Case 1: both $W^{\pm}$ near on-shell
- Case 2: both $W^{\pm}$ off-shell
- Case 3: one $W^{\pm}$ near on-shell

Only Case 1 has non-interference. Off-shell effects are suppressed by the width.

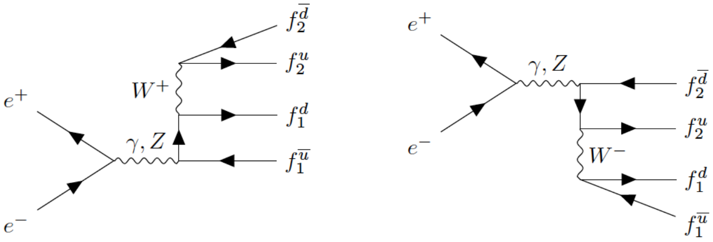
Off-shell effects

$\lambda_{12}\lambda_{34}\lambda_{+}\lambda_{-}$	$\sum_X M_X^{\lambda^\pm}/4\pi\hat{\alpha}$
$00-+$	$\frac{\sin\theta}{2\sqrt{s_1 s_3}}\left[\frac{1}{c_{\hat\theta}^2}+\left(\delta\kappa^{Z\alpha}-\delta F_2^{Z\alpha}\right)y\right]$
$\pm\pm-+$	$-\sin\theta\left[\frac{x^2}{c_{\hat\theta}^2}+\frac{y\,\delta\lambda^{Z\alpha}}{2}+\left(\delta g_1^{Z\alpha}-\delta F_2^{Z\alpha}-(s_1+s_3)\frac{\lambda_{Z\alpha}}{2}+\frac{\delta\lambda_Z}{2\,c_{\hat\theta}^2}\right)y\,x^2\right]$
$\pm 0-+$	$-\frac{(1\pm\cos\theta)\,x}{\sqrt{2s_3}}\left[\frac{1}{c_{\hat\theta}^2}+\frac{y}{2}\left(\delta g_1^{Z\alpha}-2\delta F_2^{Z\alpha}+\delta\kappa^{Z\alpha}+s_3\,\delta\lambda^{Z\alpha}\right)\right]$
$0\pm-+$	$\frac{(1\mp\cos\theta)\,x}{\sqrt{2s_1}}\left[\frac{1}{c_{\hat\theta}^2}+\frac{y}{2}\left(\delta g_1^{Z\alpha}-2\delta F_2^{Z\alpha}+\delta\kappa^{Z\alpha}+s_1\delta\lambda^{Z\alpha}\right)\right]$
$00+-$	$\frac{\sin\theta}{2\sqrt{s_1 s_3}}\left[\left(\frac{s_{\hat\theta}^2-c_{\hat\theta}^2}{2\,c_{\hat\theta}^2\,s_{\hat\theta}^2}\right)+\frac{s_1+s_3}{2\,s_{\hat\theta}^2}+\left(\delta\kappa^{Z\alpha}-\frac{\delta\kappa_Z}{2\,s_{\hat\theta}^2}+\frac{2\,\delta\bar{g}_W^\ell}{s_{\hat\theta}^2}-\delta F_2^{Z\alpha}\right)y\right]$
$\pm\pm+-$	$-\frac{\sin\theta}{2}\left[\left(1-\frac{1}{2s_{\hat\theta}^2}\right)\delta\lambda_Z-\delta\lambda_\alpha\right]y$
$\pm 0+-$	$\frac{(1\mp\cos\theta)\,x}{2\sqrt{2s_3}}\left[\left(\frac{s_{\hat\theta}^2-c_{\hat\theta}^2}{c_{\hat\theta}^2\,s_{\hat\theta}^2}\right)+\frac{s_1}{s_{\hat\theta}^2}+\frac{s_3}{s_{\hat\theta}^2}\frac{1\pm 2+3\cos\theta}{1+\cos\theta}-y\frac{\left(\delta g_1^z+\delta\kappa_z+s_3\,\delta\lambda_z\right)}{2s_{\hat\theta}^2}\right.$
	$\left.-y\left(\delta F_1^{Z\alpha}-\frac{4\,\delta\bar{g}_W^\ell}{s_{\hat\theta}^2}-\left(\delta g_1^{Z\alpha}+\delta\kappa^{Z\alpha}+s_3\,\delta\lambda^{Z\alpha}\right)\right)\right]$
$0\pm+-$	$-\frac{(1\pm\cos\theta)\,x}{2\sqrt{2s_1}}\left[\left(\frac{s_{\hat\theta}^2-c_{\hat\theta}^2}{c_{\hat\theta}^2\,s_{\hat\theta}^2}\right)+\frac{s_3}{s_{\hat\theta}^2}+\frac{s_1}{s_{\hat\theta}^2}\frac{1\mp 2+3\cos\theta}{1+\cos\theta}-y\frac{\left(\delta g_1^z+\delta\kappa_z+s_1\,\delta\lambda_z\right)}{2s_{\hat\theta}^2}\right.$
	$\left.-y\left(\delta F_1^{Z\alpha}-\frac{4\,\delta\bar{g}_W^\ell}{s_{\hat\theta}^2}-\left(\delta g_1^{Z\alpha}+\delta\kappa^{Z\alpha}+s_1\,\delta\lambda^{Z\alpha}\right)\right)\right]$
$\pm\mp+-$	$\frac{(\mp 1+\cos\theta)\sin\theta}{2\,s_{\hat\theta}^2(1+\cos\theta)}$

Table 1: Expansion in $x, y < 1$ for the near on-shell region of phase space of the CC03 diagrams approximating $\bar\psi\psi\to\bar\psi'_1\psi'_2\bar\psi'_3\psi'_4$. For exactly on-shell intermediate $W^\pm$ bosons $s_1 = s_3 = 1$. We have used the notation $\delta F^i_{Z\alpha} = (\delta F_i^Z + \delta F_i^\alpha)/4\pi\hat\alpha$, $\delta\lambda^{Z\alpha} = \delta\lambda_Z - \delta\lambda_\alpha$, $\delta\kappa^{Z\alpha} = \delta\kappa_Z - \delta\kappa_\alpha$ and $\delta g_1^{Z\alpha} = \delta g_1^Z - \delta g_1^\alpha$.

Gauge invariance

To ensure gauge invariance, we include single resonant diagrams



This does not affect the other results.

Narrow width approximation and the SMEFT expansion

The narrow width approximation is widely used;

$$\left|\frac{1}{s-\hat{m}_W^2+i\hat{\Gamma}_W\hat{m}_W}\right|^2 \to \frac{\pi}{\hat{\Gamma}_W\hat{m}_W}\delta(s-\hat{m}_W^2). \tag{11}$$

In the SMEFT the propagator is

$$\frac{1}{s-\overline{m}_W^2+i\overline{\Gamma}_W\overline{m}_W} \tag{12}$$

where $\overline{m}_W = \hat{m}_W + \delta m_W$, where bar denotes SMEFT quantities, hat denotes quantities related to the input parameters by SM relations, and δm_W contains dimension 6 effects.

Should we perform the SMEFT expansion before or after the narrow width approximation?

By first doing the narrow width approximation:

$$\left|\frac{1}{s-\overline{m}_W^2+i\overline{\Gamma}_W\overline{m}_W}\right|^2 \to \frac{\pi\delta(s-\hat{m}_W^2)}{\hat{\Gamma}_W\hat{m}_W}\left(1-\frac{\delta m_W^2}{2\hat{m}_W^2}-\frac{\delta\Gamma_W}{\hat{\Gamma}_W}\right). \tag{13}$$

Reversing the order of operations

$$\left|\frac{1}{s-\overline{m}_W^2+i\overline{\Gamma}_W\overline{m}_W}\right|^2 f(s) \to \frac{\pi f(\hat{m}_W^2)}{\hat{\Gamma}_W\hat{m}_W}\left(1-\frac{\delta m_W^2}{2\hat{m}_W^2}-\frac{\delta\Gamma_W}{\hat{\Gamma}_W}\right) + \frac{\pi f'(m_W^2)}{\hat{\Gamma}_W\hat{m}_W}\delta m_W^2. \tag{14}$$

Narrow width approximation and SMEFT expansion

The narrow width approximation and the SMEFT expansion do NOT commute in general.

Only by using $\hat{m}_W$ as an input parameter, the so-called $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme, will the commutation property be restored.

Summary

- For electroweak diboson production the SM and the SMEFT interference vanishes in on-shell regions of phase space
- However, for off-shell regions of phase space, interference is restored
- The narrow width approximation and the SMEFT expansion do not commute in general

Main message

We need to work hard, be careful and consistent when looking for signs of New Physics.